

# Superhorizon Fluctuations, CMBR and Relativistic Heavy Ion Collisions

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References: Phys. Rev. C **77**, 064902 (2008)  
Phys. Rev. C **81**, 034903 (2010)

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- Correspondence between the physics of Heavy Ion Collisions and Cosmic Microwave Background Radiation
- Importance of CMBR data analysis technique in the flow analysis in Heavy Ion Collisions.

Similarities in the nature of density fluctuations in early universe and the plasma in relativistic heavy ion collisions:

## Superhorizon fluctuations

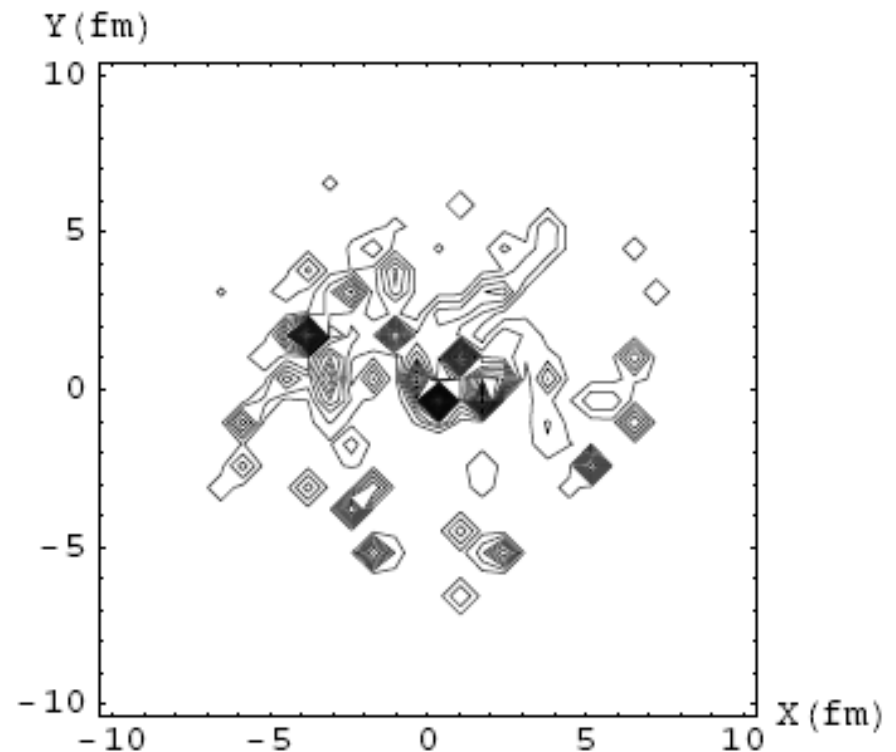
In universe: Inflation

In RHICE?

Consider central collision

Initial transverse energy  
density fluctuations at 1fm  
From HIJING

Nucleon size  $\sim 1.6$  fm  
horizon at thermalization  $\sim 1$ fm



Central Au - Au  
Collision

C M Energy 200 GeV

## **Inflationary density fluctuations and CMBR anisotropies:**

In the universe, density fluctuations with wavelengths of superhorizon scale have their origin in the inflationary period.

Quantum fluctuations of sub-horizon scale are stretched out to superhorizon scales during the inflationary period.

During subsequent evolution, after the end of the inflation, fluctuations of sequentially increasing wavelengths keep entering the horizon.

The largest ones to enter the horizon, and grow, at the stage of decoupling of matter and radiation lead to the first peak in CMBR anisotropy power spectrum.

## Physics of CMBR Peaks

Two most crucial aspects of the inflationary density fluctuations which gave rise to remarkable acoustic peaks in CMBR:

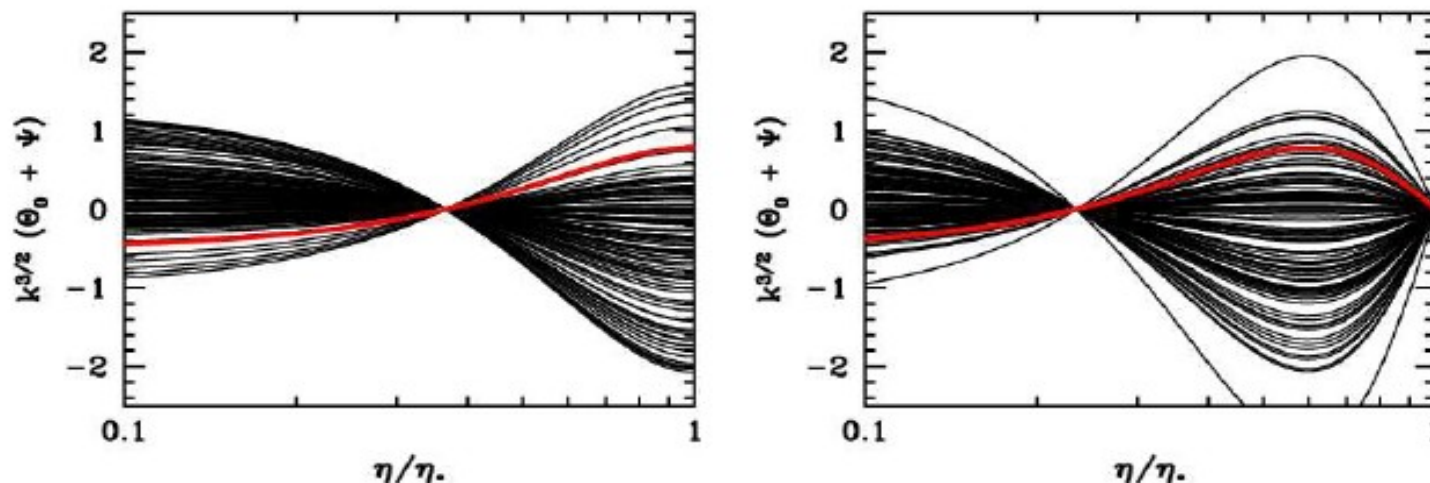
**coherence and acoustic oscillations**

Inflationary density fluctuations when stretched out to superhorizon scales are frozen out dynamically.

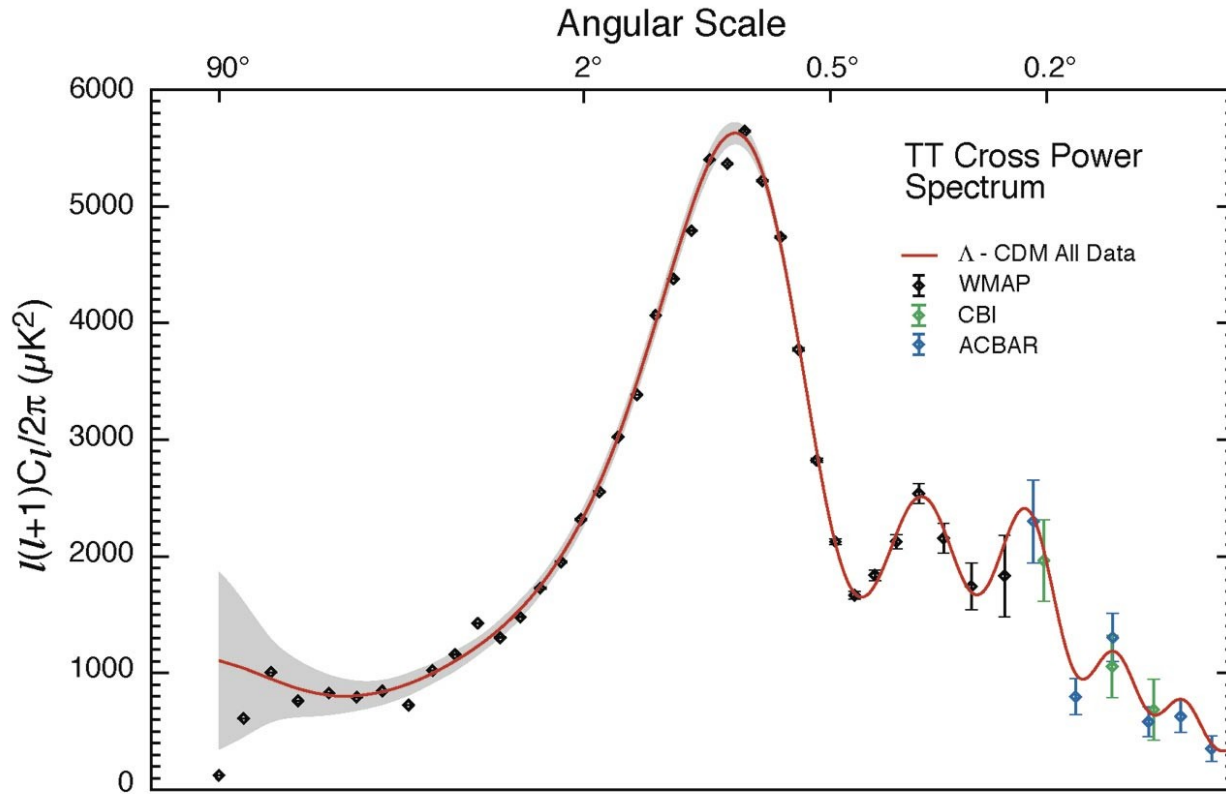
Later when they re-enter the horizon and start growing due to gravity and subsequently start oscillating due to radiation pressure, the fluctuations start with zero velocity.

For oscillation, it means that only  $\cos(\omega t)$  term survives.

All fluctuations of a given wavelength are phase locked.



# CMBR Acoustic Oscillations



Plot shows variance of various spherical harmonic components  $Y_{lm}$  as a function of  $l$ .

## Coherence in RHICE:

**The transverse velocity of the fluid to start with is zero.**

Initial state fluctuations in parton position and momenta may give rise to some residual velocities at earlier stages

But for wavelengths larger than the nucleon size, due to averaging, it is unlikely that the fluid will develop any significant velocity at thermalization.

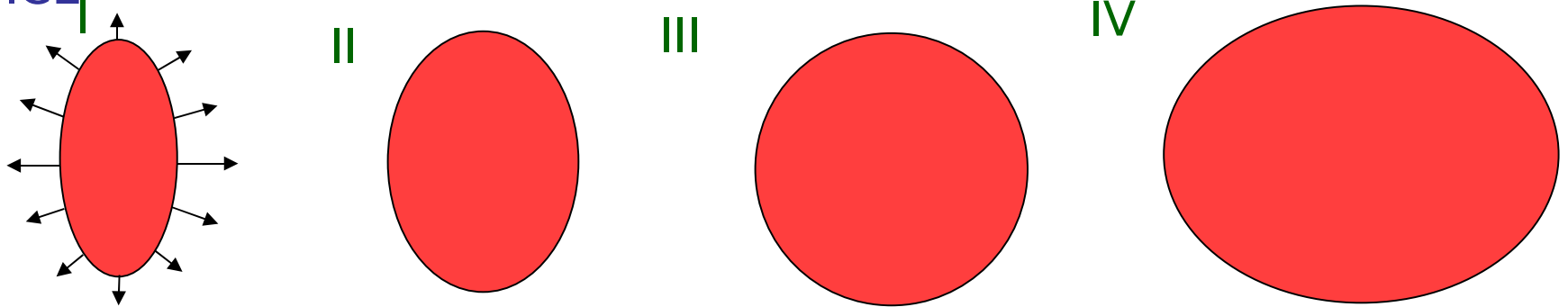
Larger wavelength modes those which enter (sound) horizon at times much larger than equilibration time may get affected due to the build up of the radial expansion.

Our interest is in oscillatory modes.

For oscillatory time dependence even for such large wavelength modes, there is no reason to expect the presence of  $\sin(\omega t)$  term at the stage when the fluctuation is entering the sound horizon.

**So the fluctuations are expected to be coherent.**

**Acoustic oscillations in RHICE:** There is a non-zero pressure in RHICE



The oscillation of plasma region in non-central collision.

Note: Any deviation from spherical shape is treated as a fluctuation, so the non-central collisions have a large wavelength fluctuation mode which is the elliptic mode.

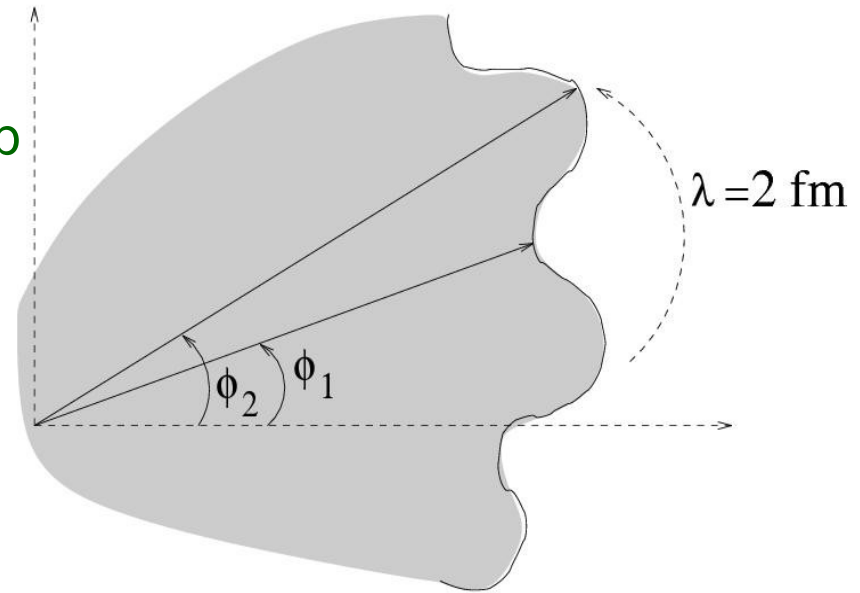
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \quad v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_y^2 + p_x^2 \rangle}$$

Not seen in hydrodynamic simulations: Development of strong radial flow.

Consider a fluctuation with small wavelength, say 2 fm.

Unequal initial pressures in the  $\phi_1$  and  $\phi_2$  directions:  
momentum anisotropy will build up  
in a relatively short time.

Spatial anisotropy should  
reverse sign in time of order  
 $l/(2cs) \sim 2$  fm



Due to short time scale of evolution here, radial expansion may still not be most dominant.

Possibility of momentum anisotropy changing sign, leading to some sort of oscillatory behavior.

## Suppression of superhorizon modes

### Acoustic horizon and development of flow:

In RHICE, the azimuthal spatial anisotropies are detected only when they are transferred to momentum anisotropies of particles.

The anisotropies of larger wavelength compared to sound horizon at freezeout are not expected to build up completely by freeze out.

So the momentum anisotropies corresponding to these wave lengths should be suppressed by a factor,

where  $H_{\text{fr}}^s$  is the sound horizon at the freezeout time  $t_{\text{fr}}$  ( $\sim 10$  fm for RHIC)

$$\frac{H_{\text{fr}}^s}{\lambda/2}$$

CMBR temperature anisotropies analyzed using Spherical Harmonics

$$\frac{\Delta T}{T}(\theta, \phi) = a_{lm} Y_{lm}(\theta, \phi)$$

Average values of these expansions coefficients are zero

due to overall isotropy of the universe

$$\langle a_{lm} \rangle = 0$$

However: their standard deviations are non-zero and contain crucial information.

$$C_l = \langle |a_{lm}|^2 \rangle$$

Apply same technique for RHICE also

## The Analysis:

Calculate the momentum anisotropies in different azimuthal bins in a fixed co-ordinate system.

Calculate the Fourier coefficients of the momentum anisotropies.

Find the root mean square values which will give different flow coefficients.

$$V_n^{rms} = \sqrt{\langle V_n^2 \rangle}$$

$$\rho(\phi') = \sum_{n=-\infty}^{\infty} v_n e^{in\phi'}$$

Conventional flow  
coefficients

$$\rho_{\psi}(\phi) = \sum_{n=-\infty}^{\infty} v_n e^{in(\phi-\psi)}$$

re-written in lab fixed  
frames

$$\tilde{v}_n(\psi) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \rho_{\psi}(\phi) e^{-in\phi} d\phi$$

Flow co-efficients in lab  
fixed frame

$$\overline{\tilde{v}_n} = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left( \frac{1}{2\pi} \int_{-\pi}^{\pi} \rho_{\psi}(\phi) e^{-in\phi} d\phi \right) d\psi$$

$$(\tilde{v}_n^{rms})^2 = \overline{\tilde{v}_n^2} = \frac{1}{2\pi} \int_{-\pi}^{\pi} d\psi \tilde{v}_n(\psi) \tilde{v}_n^*(\psi)$$

$$\tilde{v}_n^{rms} = |v_n|$$

True for elliptic flow, but not for other fluctuations.

## Calculations:

The spatial anisotropies for RHICE are estimated using HIJING event generator.

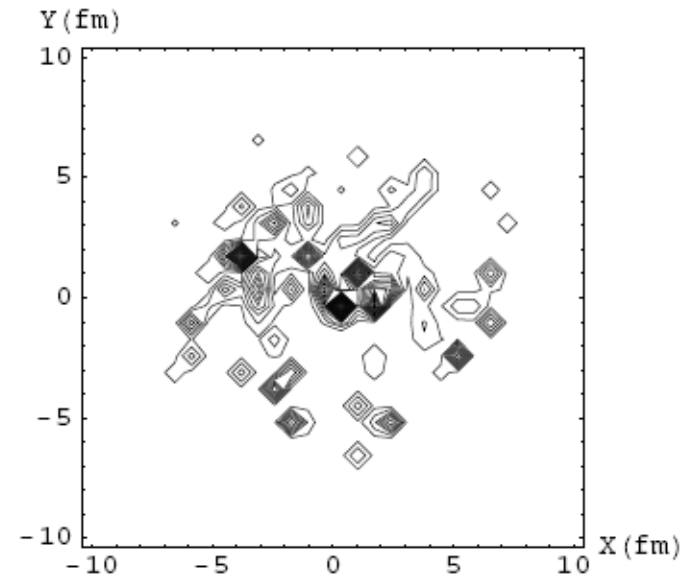
We calculate initial anisotropies in the fluctuations in the spatial extent  $R(\varphi)$  (using initial parton distribution from HIJING).

$R(\varphi)$  represents the energy density weighted average of the transverse radial coordinate in the angular bin at azimuthal coordinate  $\varphi$ .

Fourier coefficients  $F_n$  of the anisotropies are calculated as

$$\frac{\Delta R}{R} \equiv \frac{R(\phi) - \overline{R}}{\overline{R}} \quad \text{where } \overline{R} \text{ is the average of } R(\varphi).$$

Fluctuations are represented essentially in terms of fluctuations in the boundary of the initial region.



For elliptic flow we know:

Momentum anisotropy  $v_2 \sim 0.2$  spatial anisotropy  $\epsilon$ .

For simplicity, we use same proportionality constant for all Fourier coefficients: This does not affect any peak structures

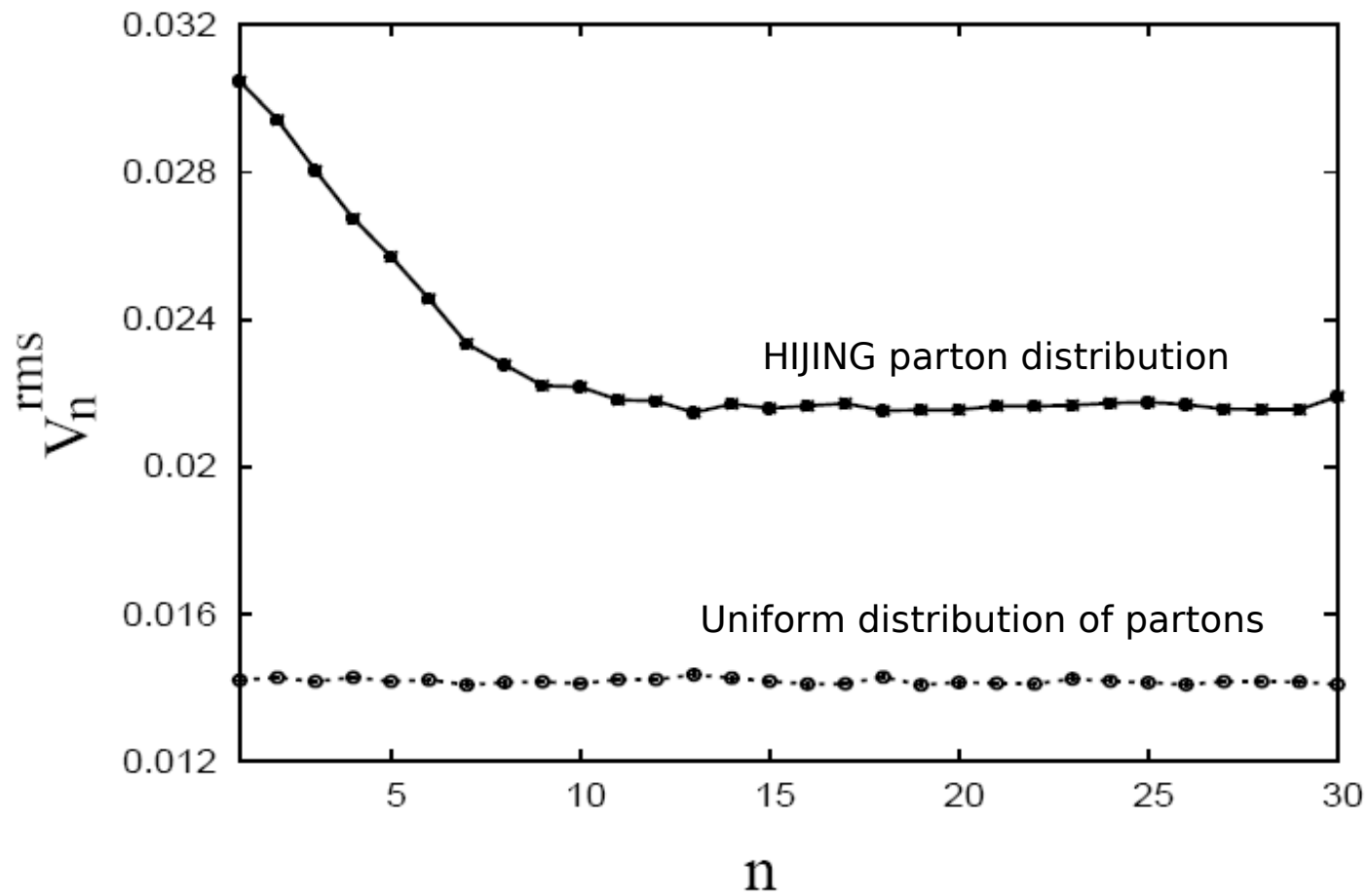
**Important:** In contrast to the conventional discussions of the elliptic flow, **we do not need to determine any special reaction plane on event-by-event basis.**

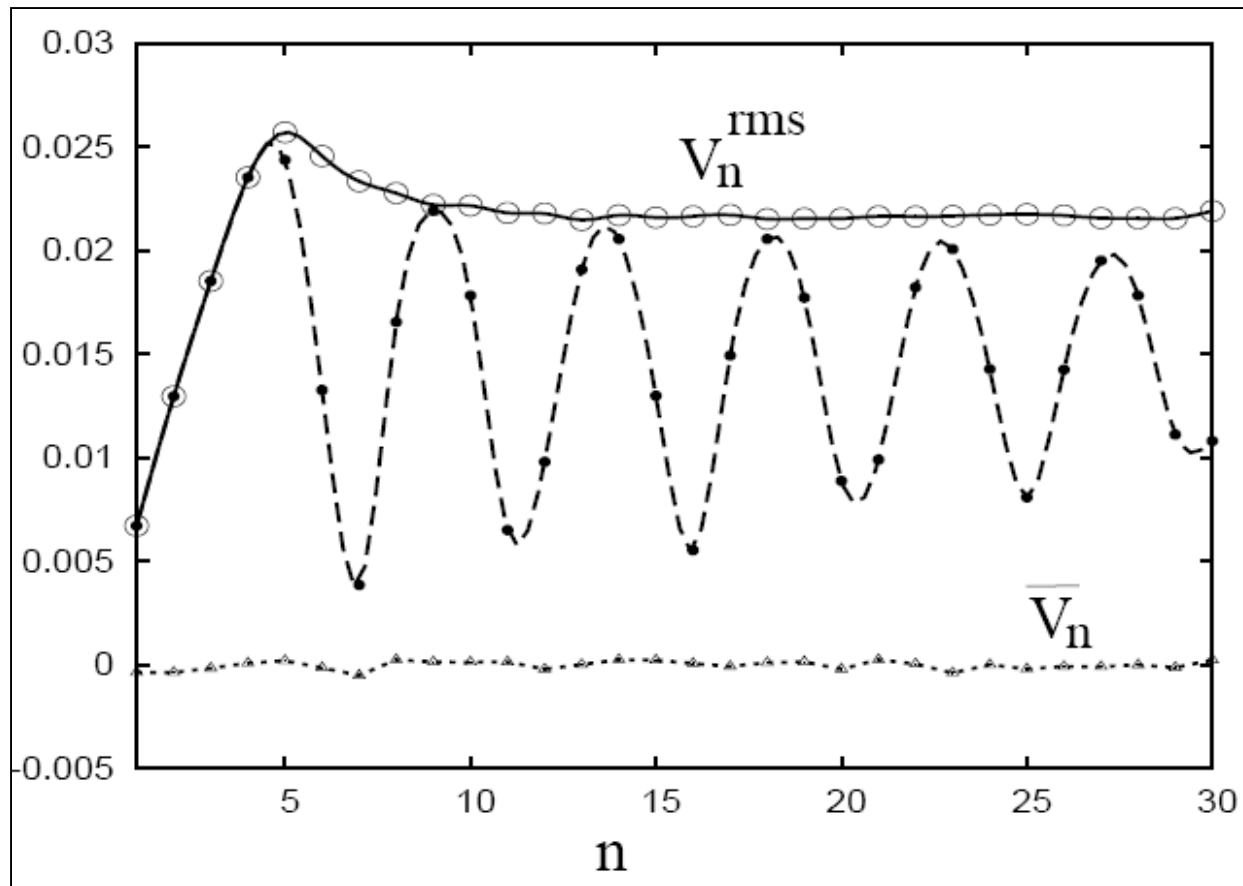
A fixed coordinate system is used for calculating azimuthal anisotropies.

This is why, as we will see, averages of  $F_n$  (and hence of  $v_n$ ) will vanish when large number of events are included in the analysis.

However, the root mean square values of  $F_n$ , and hence of  $v_n$ , will be non-zero in general and will contain non-trivial information.

## Results:

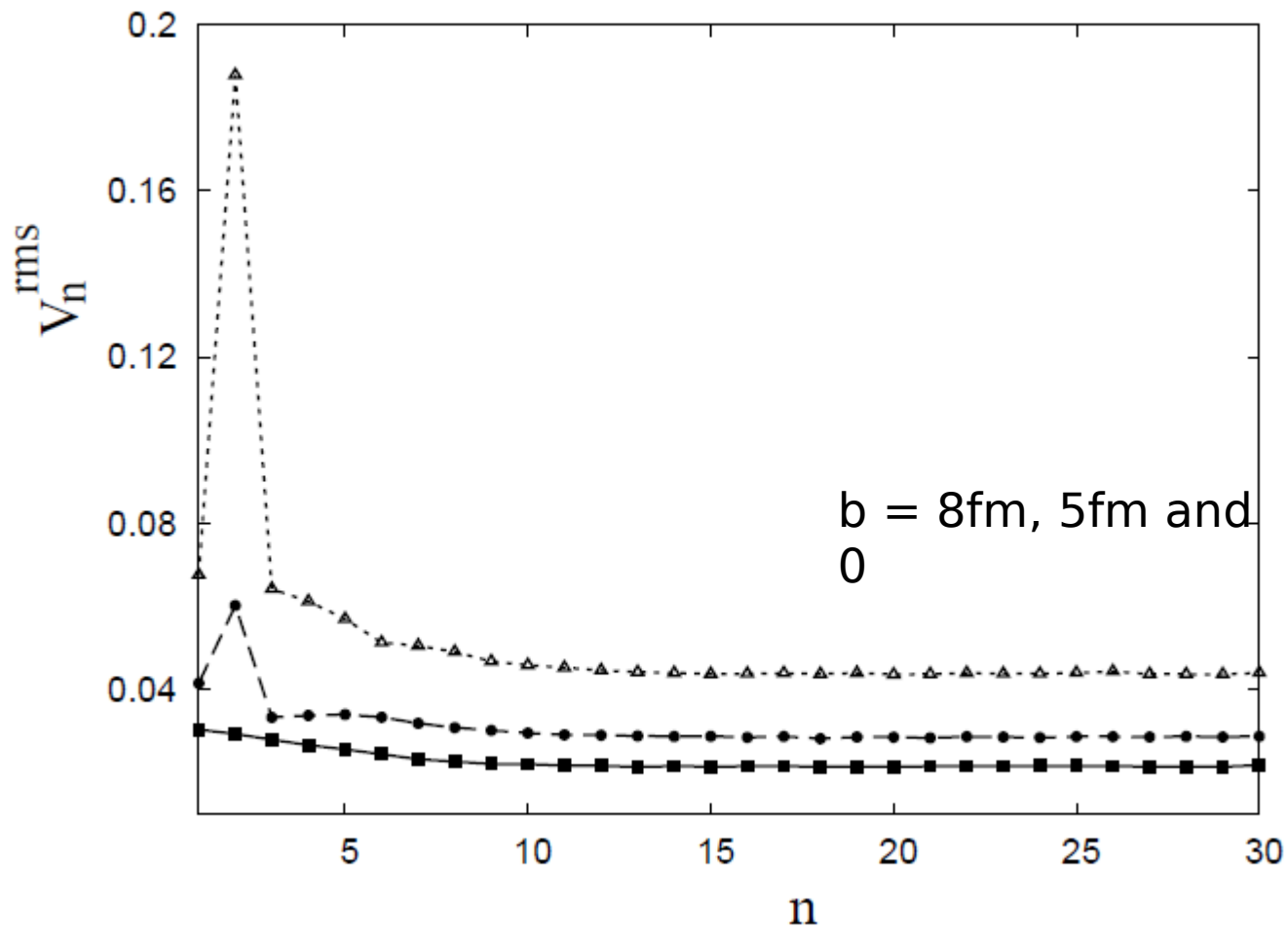


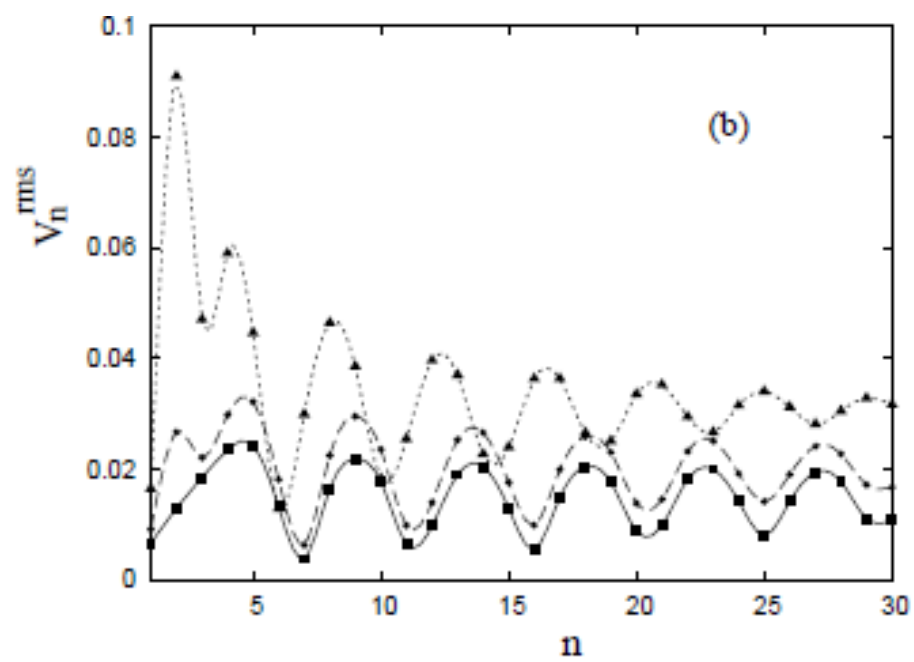
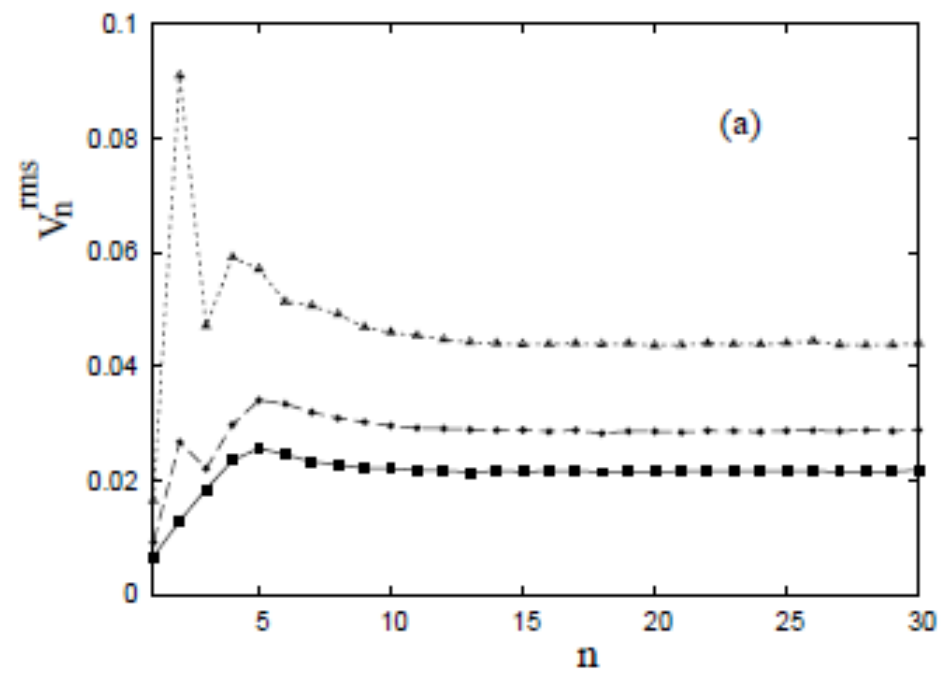


peak at  $n \sim 5$ ,  
higher modes are suppressed.

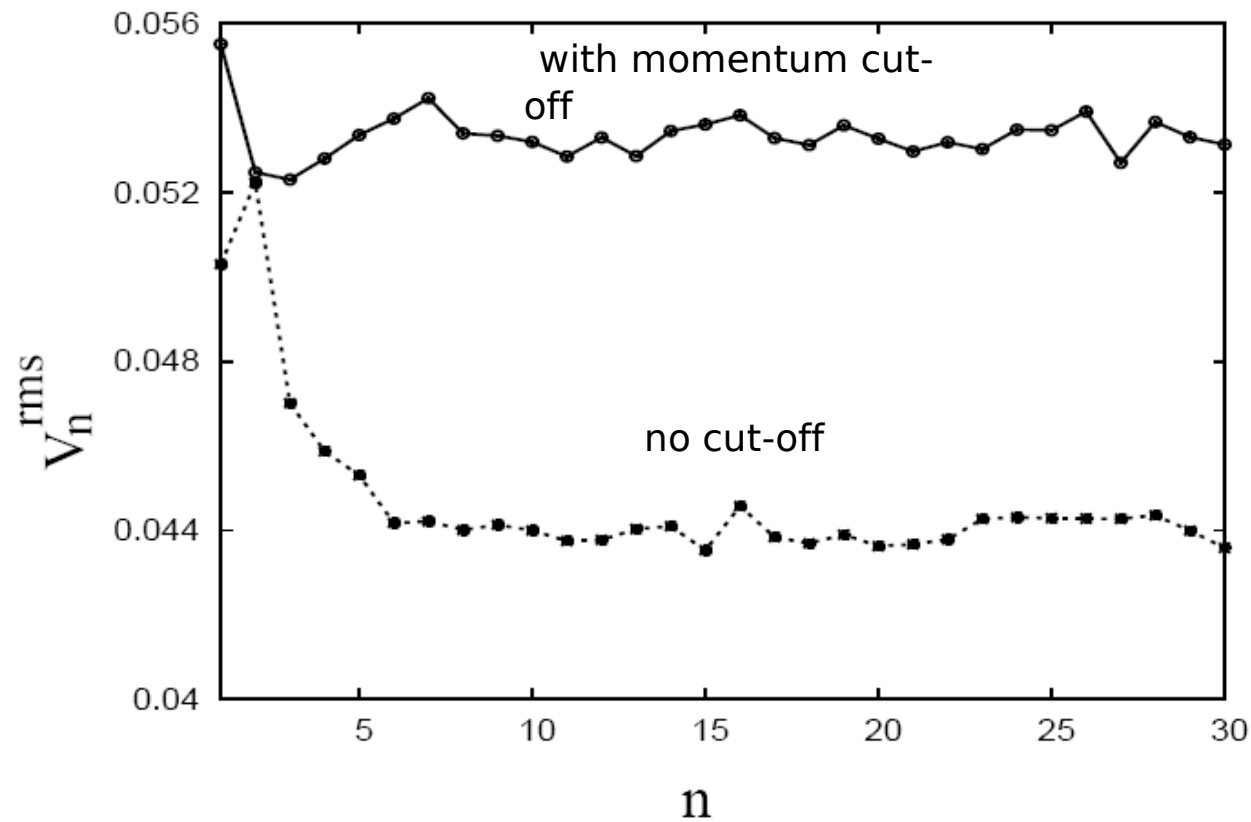
“The sound of the little bang”

# Plot for non-central collision from Hijing parton distribution





Flow coefficients calculated from HIJING final particle momenta.



No cosmic variance limitation on accuracy!

Universe: Only one CMBR sky:  $2l+1$  independent measurement for each  $l$  mode.

RHICE: Each nucleus-nucleus collision with same parameters provides a new sample. Accuracy limited only by the number of events.

Important information contained in such a plot:

overall shape of the plot : information on the early stages of evolution of the system and evolution, regime of break down of hydrodynamics (look at higher modes).

first peak : freeze-out stage, equation of state.

successive peaks : dissipative factors, nature of the phase transition if any.

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